Nanostuctured Aluminum for a Macrostructured World

Bulk nanocrystalline aluminum is an exciting class of light materials that features high strength and good ductility. Applications range from aerospace components and pressure vessels for hydrogen gas to improving the performance of ballistic armor. We have assembled a multidisciplinary team, including collaboration with the University of California at Davis, to explore the metallurgy of these innovative materials.

To begin, alloy powder is milled at cryogenic temperatures to induce severe plastic deformation (SPD). This substantially reduces the grain size within the particulate, while low temperature prevents recovery and recrystallization. Although oxide inclusions are introduced from the oxide layer covering the starting powder, the SPD refines these hard inclusions in the alloy (present in all engineering alloys) and uniformly distributes them. Milling is followed by high-temperature consolidation to produce a bulk ingot at near-full density. Subsequent rolling or extrusion at elevated temperature produces the final wrought product in the desired form: plate, bar, etc. Processing must be designed judiciously to avoid grain growth and loss of nanocrystalline structure. Since the final working steps are conventional processes, in principle, standard engineering product sizes can be produced with nanocrystalline microstructures.

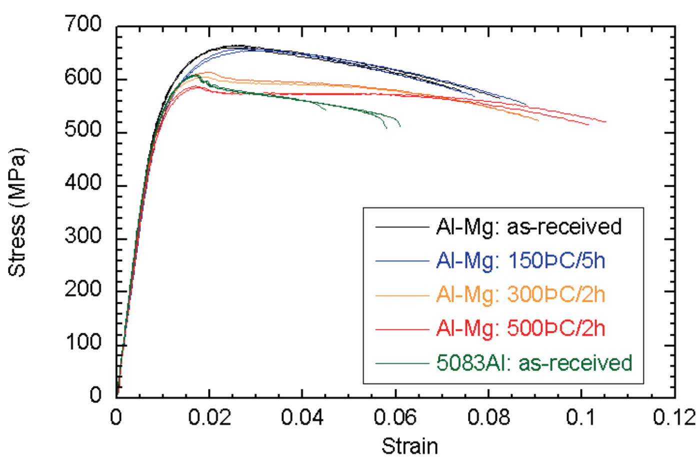


Figure 1. Tensile stress-strain curves of nanocrystalline alloys in the as-received condition and after annealing.

The strength of cryomilled aluminum alloys is clearly superior to conventional alloys and elongation is similar to high-strength alloys. The yield strengths of cryomilled 5083 aluminum alloy and an Al-Mg alloy (Figure 1) are both greater than 500 megapascal (MPa) compared to values as high as 300 MPa for these alloys in conventionally strain-hardened condition. The cryomilled material's higher strength is largely derived from its small grain size on the order of tens of nanometers (Figure 2). Moreover,

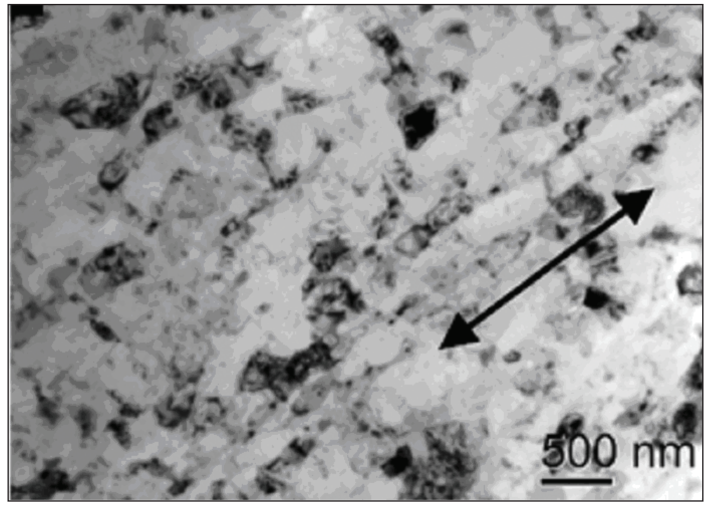


Figure 2. TEM micrograph of nanocrystalline 5083 alloy.

annealing of cryomilled materials at as much as 500 °C for two hours only modestly affects strength. This excellent thermal stability is unusual for nanocrystalline alloys and contributes obvious benefits with regard to welding and high-temperature use.

Since industry is moving toward cleaner alloys that minimize brittle second phases, cryomilling, which entrains additional second phase into the material, would appear to be folly for maintaining ductility and fracture resistance. This problem is compounded by the nanocrystalline microstructure, which inherently lacks ductility due to high strength and small grain size. Cryomilling, however, efficiently disburses

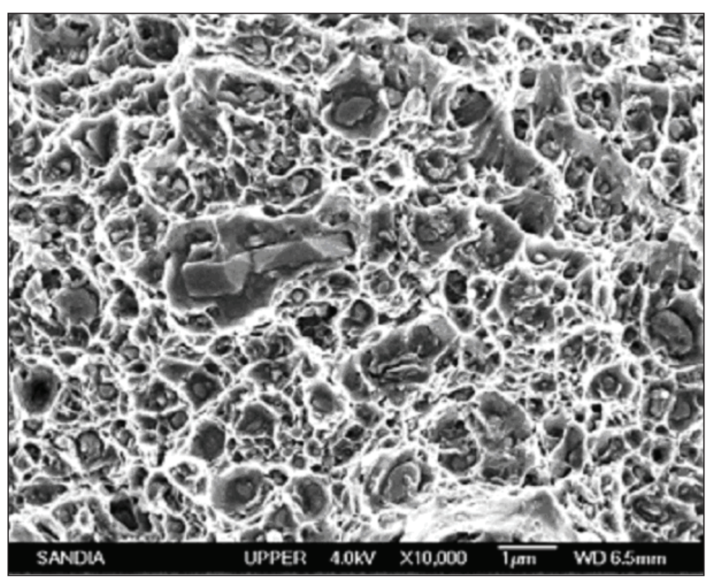
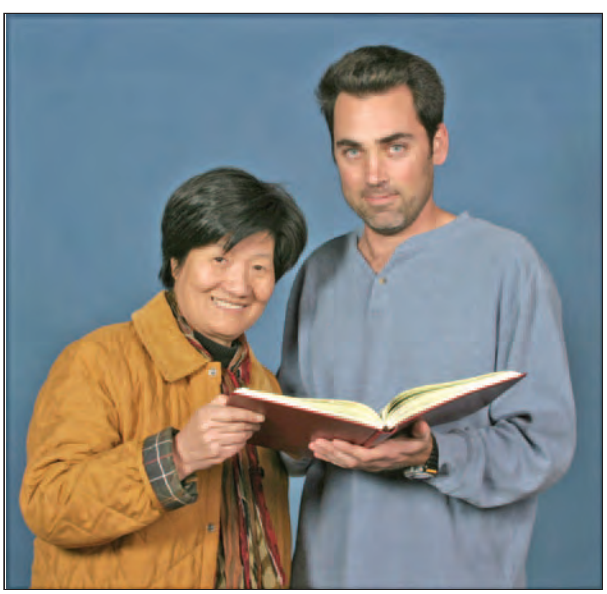


Figure 3. Fracture surface of nanocrystalline 5083 alloy.

very fine second phases, which have superior resistance to fracture compared to large, clustered particles, thus improving the overall ductility of the material.
It is the small size of these second phases that also allows them to pin grain boundaries (as well as dislocation motion) and stabilize the microstructure under thermal phenomena such as recovery and recrystallization, thus providing the thermal stability and improving strength.

In summary, bulk nanocrystalline aluminum produced by cryomilling benefits from otherwise detrimental second phases: improved strength with good ductility and excellent thermal stability. Despite preliminary analysis, deformation mechanics and constitutive behavior are far from understood. We are developing models for simulating microstructural evolution (Doug Bammann, 8763), quantifying the physical metallurgy (Gene Lucadamo and Nancy Yang, 8773) and understanding the mechanical metallurgy (Chris San Marchi, 8772) in nanocrystalline aluminum produced in collaboration with the University of California at Davis (Prof. Enrique Lavernia).



Chris San Marchi, right, is the lead principal investigator for this program funded by a Laboratory Directed Research and Development grant and Research Foundations. He received his Ph.D. from MIT in 1997 and came to Sandia in 2002. His research interests include hydrogen effects in materials and microstructural design of engineering materials. Nancy Yang, left, is co-principal investigator on this program and manages the electron optics group at Sandia/California. She has been at Sandia for 19 years.